Title**:** A signal processing, Result management and Visualization system for Evaluation of Long Term Dynamic Behavior of Bridges

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ABSTRACT

This paper describes a system developed in LabVIEW environment to monitor the long term dynamic behavior of bridges. This system comprises three main parts: an automated signal processing toolkit, including automated vibration level detection and system identification; a database to organize the results, in text and graph format, generated from the signal processing toolkit; and a user-friendly results visualization toolkit. This system automatically processes, both in real-time and offline model, the signals acquired in every setup and generates the corresponding daily and monthly variation of vibration levels and modal parameters. The usefulness of this system is illustrated with an application to data continuously acquired by the permanent dynamic monitoring system of a Portuguese lively footbridge.

INTRODUCTION

Structural Health Monitoring (SHM) has become a major international research topic in recent years in Civil Engineering. The main subjects in this research area are signal acquisition and communication, signal processing and system identification, data management and storage, as well as feature extraction for damage diagnose [1]. Full automation of SHM procedures is necessary and remote access based on Internet is an inevitable trend [2].

In this context, this paper describes a system developed in LabVIEW environment for automated signal processing, results organization and visualization, at the Laboratory of Vibrations and Monitoring (ViBest, www.fe.up.pt/vibest) of the Faculty of Engineering of University of Porto (FEUP). The potential of this system is illustrated by applying it to Pedro e Inês footbridge, an innovative lively footbridge recently constructed at Coimbra, in Portugal.

AUTOMATED SIGNAL PROCESSING, RESULTS MANAGEMENT AND VISUALIZATION SYSTEM

The development of an automated signal processing, system identification, data management and results visualization system for SHM faces three main challenges: (1).the automatic signal processing and system identification; (2).the efficient organization of the massive amount of signal files and analysis results; (3) and the easy visualization and remote access of analysis results via Internet. Therefore, the

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system developed in this work is divided in three parts (Figure.1): First of all, an automated signal processing and system identification toolkit is proposed without any manual operation and generating a series of results. Secondly, those analysis results, including text and graphic files, are automatically saved in a database based on common folders in Window XP system, in order to conveniently organize a huge amount of results. Thirdly, a user-friendly graphic user interface (GUI) toolkit is developed to immediately access the analysis results by specifying time values and other options. This GUI toolkit can be easily published in the framework of a webpage and is profitable in remote monitoring by Internet.

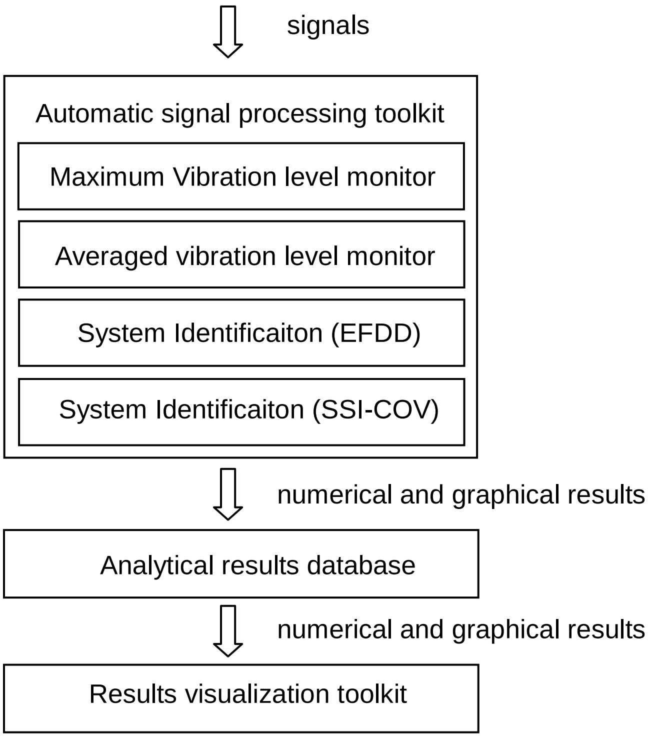


Figure 1. Framework of the developed automated signal processing, results management and visualization system

Automated signal processing toolkit

The automated signal processing toolkit searches the latest setup signal file transmitted by the data acquisition system, detects maximum vibration amplitudes both in vertical and lateral directions, identifies the modal parameters continuously by *automated enhanced frequency domain decomposition* (EFDD) and *covariance driven stochastic subspace identification* (SSI-COV) methods. Based on continuously processed results in each setup, daily and monthly variations and statistical distributions of maximum vibration amplitudes, as well as of modal parameters are also generated automatically. Owing to space limitation, the algorithms of maximum vibration detection and system identification are not described here, this paper just presenting the main steps of processing and the main results achieved, in order to illustrate the usefulness of this toolkit.

The procedure used in the automated signal processing toolkit comprises the

following steps:
(1).Automatic and continuous search of the latest signal file generated by the data acquisition system; (2).Detection of the maximum vibration level: the envelope of the acceleration signals is identified by a wavelet-based peak detection algorithm [3-4] (Fig.2), the mean of the envelope values in 1 second is evaluated (Fig.3) and the maximum vibration level is identified by picking the peak of mean values. (3). According to the maximum vibration level identified in each setup, the statistical distribution of maximum vibration in each day and each month is organized. (4). Following maximum vibration detection, average vibration levels in each hour are evaluated, and corresponding results are saved to database. (5).Automated EFDD method proposed by [5-7] is also implemented in this toolkit. In the process of calculating the output average PSD matrices, Hanning window is employed, with a window length of 8192 points and an overlapping of 50%. A singular values spectrum is automatically generated based on one hour of response, as shown in Fig.4. The natural frequencies are identified by simply picking the peaks. (6).According to the identified frequencies in each hour, the identified first modal frequencies in one day is plotted, as shown in Fig.5. Based on the daily frequency results, the plots of monthly distribution of the first modal frequencies are also presented, as shown in Fig.6. All graphics of daily variation of frequency in one month are plotted in this figure. (7).Automated modal damping estimation based on EFDD method is also integrated in this toolkit. Figure 7 shows a typical free decay curve obtained with this technique. The number of poles for curve fitting and residues of curve fitting are used to evaluate the quality of damping estimation results. Daily and monthly statistical distributions of modal damping ratios are shown in Fig.8-9. (8).Beyond the application of the EFDD method, the acquired signals are also processed by the covariance driven Stochastic Subspace Identification (SSI-COV) method [8] and results are also saved to database automatically. (9).All figures are automatically saved to database with specified directory in PNG format. The corresponding numerical results consisting of the values of maximum vibration levels, averaged vibration levels, natural frequencies and modal damping ratios, as well as the information when and where they are observed are also saved to database in TEXT format.

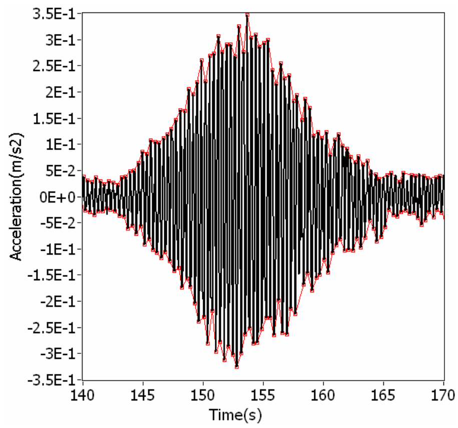


Fig.2. Acceleration signal and its envelope (zoom)

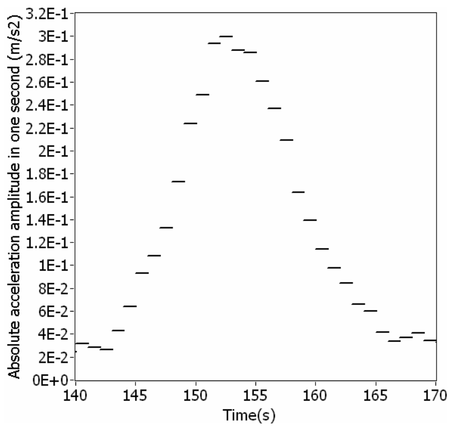
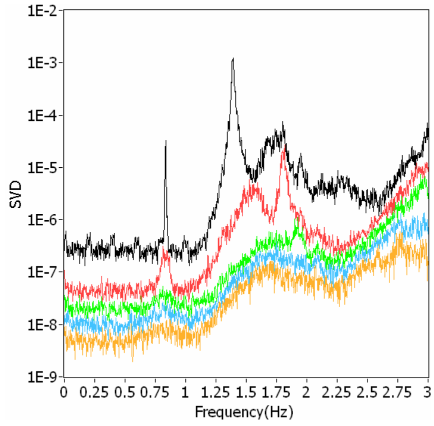


Fig.3. Mean of absolute values of the envelope (zoom)



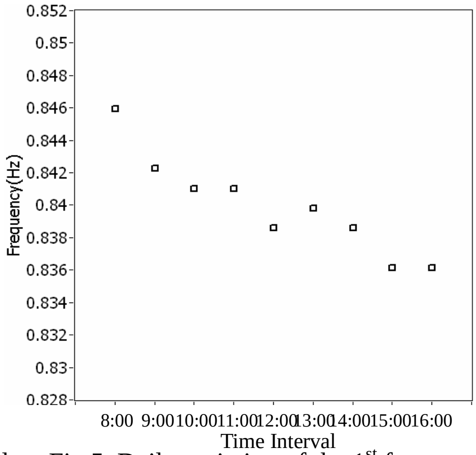
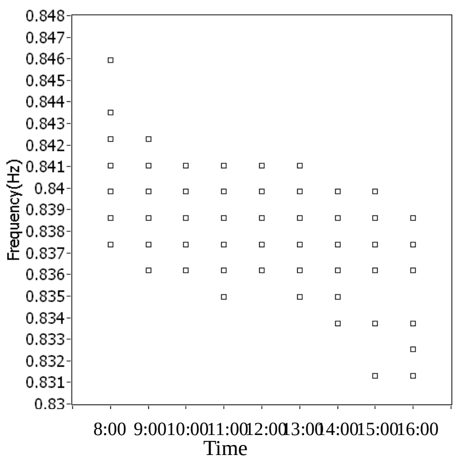


Fig.4. Typical singular values spectrum produced by one hour vertical vibration signal

Fig.5. Daily variation of the 1st frequency identified by EFDD method



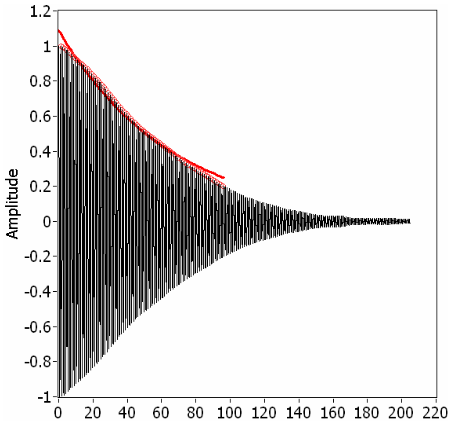
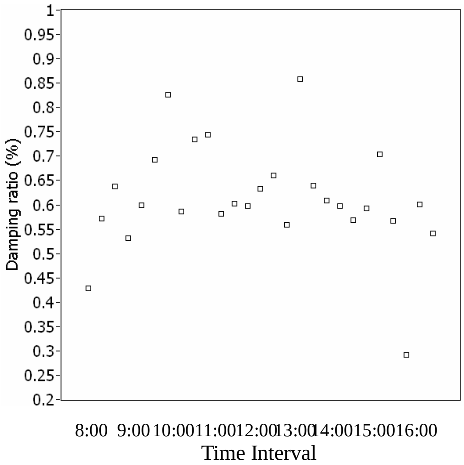


Fig.6. Monthly variation of the 1st natural frequency identified by EFDD

Fig.7. Free decay curve and corresponding envelope fitting



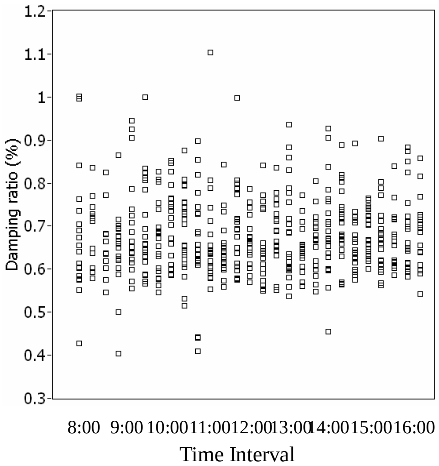


Fig.8. Daily variation of the 1st modal damping ratio identified by EFDD

Fig.9. Monthly variation of the 1st modal damping ratio identified by EFDD

Results management database

The results management system is a series of cascading hierarchical folders created in Window XP system. The main folder consists of four subfolders ‘maximum’, ‘averaged’, ‘EFDD’ and ‘SSI’ for saving the information stemming from the corresponding signal processing operations. They have similar structure though they integrate different subfolders for saving different results. All specified directories for saving the processed results are conveniently implemented in the automated signal processing toolkit. When this toolkit operates, the results are saved to local disk automatically. It is convenient to create new folders, as well as the corresponding save directories used by the automated signal processing toolkit for application of the monitoring system to other structures. The size of each PNG file is no more than 15Kb and the TEXT file is less than 10Kb.

Results visualization toolkit

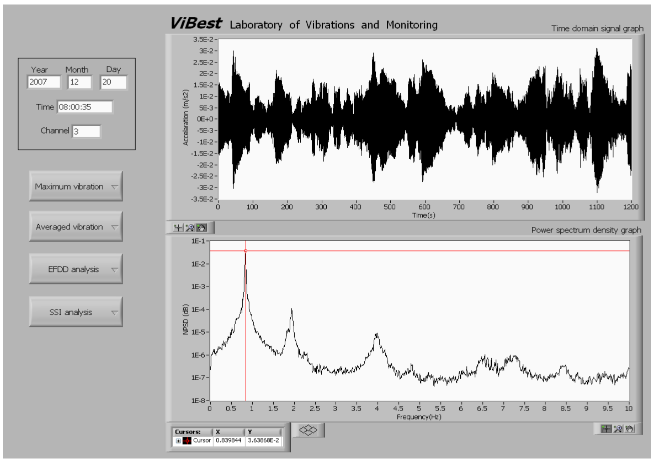


Figure.10 Main panel of results visualization toolkit

With the purpose of allowing a rapid and easy access of the user to long term dynamic monitoring results, the results visualization toolkit was specially designed with a main panel and a series of subpanels. The main panel comprises three components (Fig.10): five numerical indicators, four pull down menus and two graph indicators. The user can specify different time and channels in five numerical indicators to load the corresponding acceleration signals using the ‘Time domain signal graphic’ indicator. In the meanwhile, the graphic of the power spectrum density (PSD) is also calculated and shown in ‘Power spectrum density graphic’ indicator. A red cursor in this graphic indicator can be used to detect the frequency values around each peak in PSD graphic and the frequency content of the vibration signal is clarified. The user can also apply ‘zoom’ and ‘move’ functions to search some more interesting parts of the plots shown using two graphic indicators. Four pull down menus were included to load the results, both in PNG format and TEXT format, pre-processed by automated signal processing toolkit and saved in the local database. The user can click the menus and choose different options and enter a series of subpanels. In this way, the user can load all pre-processed results. The graphics are loaded directly and the numerical results are shown in table indicator on the left side of subpanel, allowing the user to easily examine the numerical results, as well as the information when and where they occurred. By pushing ‘Return’ button in red, the user goes back to the main panel and makes another choice. The results visualization toolkit can be linked by webpage, which permits the user to easily control this toolkit and access long term monitoring results via Internet.

APPLICATION TO PEDRO AND INÊS FOOTBRIDGE

The new footbridge Pedro e Inês, recently constructed in Coimbra, with a total length of 275m, is formed by a parabolic central arch with a span of 110m and two half lateral arches, in steel, supporting with total continuity a composite steel-concrete deck (Figure 11). The anti-symmetry of both arch and deck cross-sections along the longitudinal axis of the bridge is a unique feature of this bridge, leading to the creation of a central square with 8mx8m at mid-span.
Six groups of Tuned Mass Dampers (TMDs) were installed with the main purpose of monitoring possible excessive vibration caused by pedestrians and six acceleration transducers were installed inside the deck in correspondence with the location of the TMDs to monitor the vibration level (Figure.12) [9]. An automatic data acquisition system was developed based on LabView software to record the acceleration signals and generate a setup file every 20 minutes. This system has been operating normally since 1st June 2007. The data communication system is based on a FTP server, which automatically transmits the latest signal setup file via ADSL line from Coimbra to the computer server at FEUP, Porto [10].

Figure.11 General view of Pedro e Inês footbridge

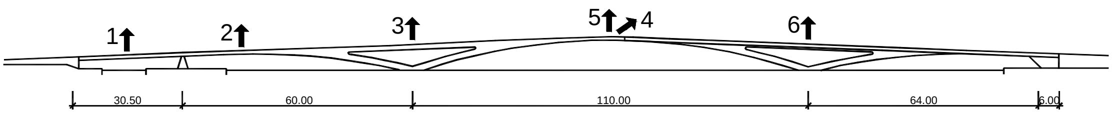


Figure.12 Location of acceleration sensors

To process the successive signal files transmitted from Coimbra, the signal processing, results management and visualization system, briefly described in this paper, was utilized. Partial results have been already shown in Figures 2-9.With help of this toolkit, several entities (e.g. designer, bridge owner and FEUP) can easily access complete vibration information both in time and frequency domain. Figures 13 and 14 present all daily maximum vertical and lateral measured accelerations. No excessive vibration was observed from 1st June 2007 to 28th February 2008. The variations of the first two natural frequencies in this time period are also shown in Figures 15-26. The total size of the generated results from June 2007 to February 2008 is about 4Gb, which is acceptable for a normal PC computer.

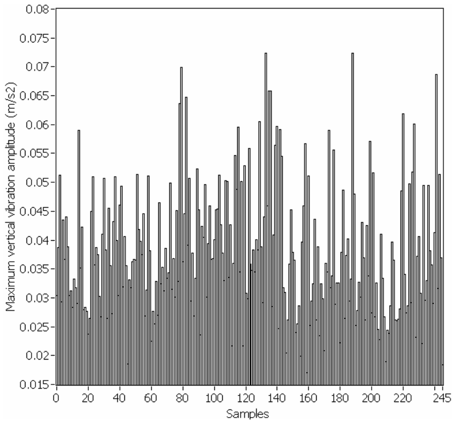


Fig.13. Vertical daily maximum acceleration

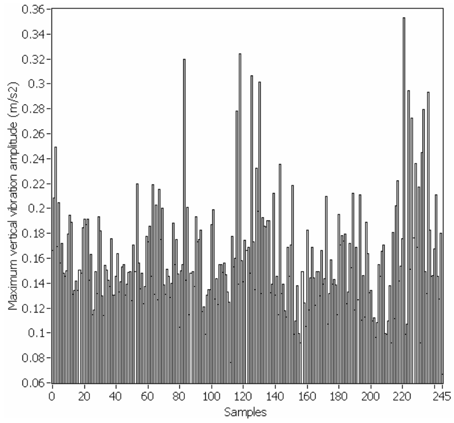


Fig.14. Lateral daily maximum acceleration

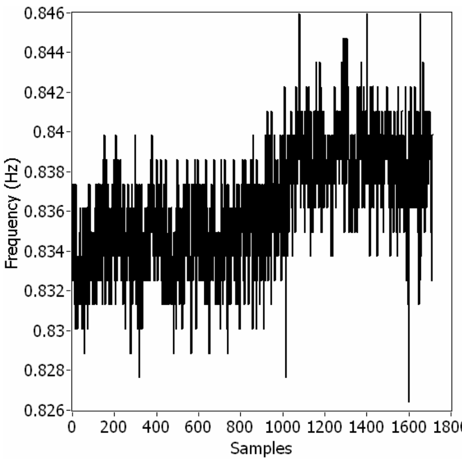


Fig.15. Variation of the 1st natural frequency

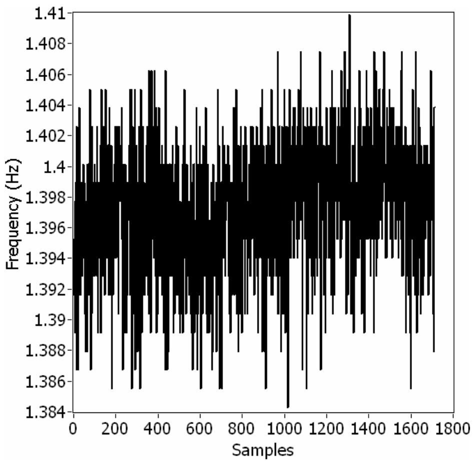


Fig.16. Variation of the 2nd natural frequency

CONCLUSIONS AND FUTURE WORK

This paper describes an automatic LabView based signal processing, results management and visualization system, for long-term dynamic monitoring of bridges. This system can automatically search and process the latest signal files acquired, organize the results in a database and publish them in suitable format. The obvious benefit of this system is that all key procedures of signal processing and system identification are automatically implemented and results achieved are saved both in text and graphic format (Text file & Portable Network Graphic file), and so different users can easily access them and analyze the monitoring results.

Recent implementation of this system in the permanent dynamic monitoring of the lively Pedro e Inês footbridge, in Portugal, allowed the appropriate illustration of the potential of this system.
This system will be used to support the vibration-based structural health monitoring of bridges and special structures, aiming in particular to analyze and remove the effect of environmental factors (e.g. temperature) and extract damage indicators.

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